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# EXTERNALLY COMPENSATED CRYSTAL OSCILLATOR (ECXO) STUDY

TRACOR, Inc.

O. J. Baltzer Charles S. Stone



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The primary objective of this contract was an investigation and exploratory development of an externally compensated crystal oscillator (ECXO) in which frequency-temperature compensation of the C-mode frequency of an SC-cut quartz crystal is achieved by utilizing the concurrent B-mode frequency as a highly sensitive digital temperature sensor. The digitized B-mode output, used in conjunction with a microcomputer and a stored frequency/temperature "look-up" table or a suitable compensation algorithm, is able to provide precise and accurate clock corrections over a much wider range than that possible with a conventional TCXO oscillator (a temperature compensated oscillator which employs a voltage-variable capacitor for direct oscillator frequency control).					
Major conclusions of the investigation include:					
1. The observed repeatability and stability characteristics of the B-mode and C-mode fre-					
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quencies of the SC-cut resonators indicate that, over an operational temperature range of -55°C to +100°C, a clock accuracy of several millisecond/day should be attainable; higher accuracy probably feasible with further development and greater sophistication.

- 2. Severe B-mode activity dip at some temperature within the test range of  $-55^{\circ}$ C to  $+100^{\circ}$ C noted in most, but not all SC-cut crystals used in the test program.
- 3. Simple compensation for thermal shock effects shown to be beneficial and essential to meeting above accuracy goal; practicality of compensation for residual hysteresis effects will require further study.
- 4. Partial inadequacy of polynomial approximation for compensation purposes; if ultimate accuracy is to be achieved, operational ECXO will probably require auxilary look-up table in combination with a low order polynomial approximation algorithm.
- 5. Compensation capability does not appear to deteriorate significantly in low temperature region (in spite of the severe C-mode frequency/temperature slope at the low temperature extreme).
- 6. The phase-modulated resonance reflectometer used in this investigation offers a new, valuable instrumentation technique in present and future crystal testing applications.

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# SECTION 1

# PROGRAM DESCRIPTION

# 1.1 PROGRAM BACKGROUND AND OBJECTIVES

Advanced military communication, navigation, and identification systems are placing increasing demands for higher accuracy, lower power dissipation, smaller size, and greater reliability in component timing and frequency control systems. The unique problem of attainable clock accuracy, for example, can play a deciding role in the specification and selection of any newly proposed identification system or communication system using spread spectrum techniques. Any proposed tactical system based on a clock accuracy that can only be obtained with an atomic frequency standard is generally unacceptable. Similarly, the power requirements of the conventional oven-controlled crystal oscillator may be excessive in battery-operated applications.

More than two decades of development effort have been directed toward the development of temperature-compensated crystal oscillators (TCXO)<sup>1,2</sup>. These ovenless oscillators attempt to maintain frequency accuracy over a moderate

<sup>(1)</sup> O.J. Baltzer, "Temperature Compensation of Transitorized Crystal Oscillators", 12th Southwestern IRE Conference, Houston, Texas; April 22, 1960.

<sup>(2)</sup> V. Rosati, S. Schodowski, and R. Filler, "Temperature Compensated Crystal Cscillator Survey and Test Results", <u>Proc.</u> 37th Annual Frequency Control Symposium; 1983, pp. 501-505

temperature range by using a temperature-sensing element and a voltage-variable capacitor (varactor) to shift or "pull" the oscillator frequency in a direction to counteract the natural frequency drift of the crystal. Currently available TCXO oscillators can employ analog, digital, or even microprocessor elements for the compensation circuitry. The basic accuracy and stability of all conventional TCXO devices is limited, however, by the varactor and the basic TCXO concept itself.

This traditional approach—forced internal tuning of the oscillator—introduces operational and performance problems into any tactical system requiring highest accuracy TCXO timekeeping capability. Fortunately, there is growing recognition of an alternative technique—one in which the required tunability and time adjustment functions are obtained by means external to the oscillator: (3)

"Very frequently, the system designer is confronted with a reed to provide for frequency or time (phase) adjustability. In the past, more often than not it appeared easiest to the system designer to specify an adjustable frequency standard or clock. Crystal devices can be made tunable by adding a capacitor in parallel or in series to the quartz crystal resonator. Tunability is then achieved by varying the value of this capacitor mechanically or electrically (varactor)...

In most cases, however, it is overlooked that the addition of tunability affects the basic operation of the frequency standard or clock in a detrimental way. Frequency standards derive their high stability and accuracy from the fact that the essential control element, the quarts crystal resonator or the stomic resonator, has a high resonance Q, and that their resonance frequency is highly invariant with time or external parameter changes. The addition of a tuning capacitor, in the case of crystal secillators, or the provision for tagnetic field variability in the case of atomic resonators, virtually always degrades the performance by providing a direct coupling of the resonator to varying external influences...

It is, therefore, useful to assert that large tunability and state-of-the-art performance in frequency standards and clocks are incompatible, and to the best of the authors' knowledge have never been satisfactorily combined. In other words, we have the axiom that tunability causes deterioration of clock and oscillator performance. Instead of requiring the clock manufacturer as supply a tunable, superprecision clock, system designers should consider implementing tunability by means external to the actual clock. To this end, frequency tunability can be achieved by adding an external direct synthesizer or a second tunable oscillator with a synthesizing loop. If phase or time adjustment is desired, external phase shifting by digital or analog means should be the method of choice."

This concept of "external phase shifting by digital or analog means" can obviously be extended to an oscillator requiring temperature compensation. Should the resultant device be called a "TCXO"? Possibly. However, to avoid confusion with the traditional TCXO involving internal control by means of a varactor, the terminology "externally compensated crystal oscillator (ECXO)" appears preferable for any class of crystal oscillator in which frequency tunability of phase/time adjustment is obtained by means external to the crystal oscillator.

<sup>(3)</sup> H. Hellwig; S. Stein and F. Wells, NBS; A. Kahan, RADC Hanscom AFB, "Relationship Between the Performance of Time/Frequency Standards and Navigational/Communication Systems," Proc. 10th Annual PTTI, 1978, pp. 37-53.

In late 1979 Tracor was awarded an Air Force contract (F41608-78-G-0063 SG0103) to study the "Constancy of the Center Frequency" for the United States' concept of the NATO Identification System. It soon became apparent that accurate clock performance was a critical factor in determining the minimum useable code validity interval and related sychronization requirements in the program. In search of a suitable clock candidate capable of accurate, ovenless operation over a -55°C to +85°C range, Tracor recognized the unique and important advantages of the ECXO approach over the traditional TCXO design.

The earliest ECXO design considered by the Tracor team was fairly conventional. It was based on an AT-cut crystal oscillator with a standard thermistor used as the crystal's temperature sensing element. However, whereas in conventional TCXO units the thermistor is used to control a varactor within the oscillator's tuning circuit, the Tracor design proposed the utilization of the thermistor to control the clock's timing output by means of a digital divider/phase shifter external to the crystal oscillator.

During this study, Tracor also became aware of new developments in SC-cut crystal technology, including the significant, but at that time, little recognized, experimental work at Hewlett-Packard into the use of the temperature-sensitive

B-mode frequency of an SC-cut crystal--using the ECXO concept--for temperature compensation of the concurrent C-mode frequency. 4,5

Although this original Hewlett-Packard experimental study was limited to several laboratory oscillators using the dual B-mode and C-mode of operation, with testing restricted to the 0°C to 40°C range, the Tracor staff recognized the tremendous potential of this work. Accordingly, in submitting a Final Report to the U.S. Air Force on the proposed NIS tactical identification system, Tracor strongly recommended that further research and development be directed toward the ECXO concept as an alternative to the conventional TCXO.

In June, 1981, the Electronic Systems Division, Air Force Systems Command, Hanscom AFB, awarded Tracor a contract (Contract F19628-81-C-0087) to test and evaluate an externally compensated oscillator (ECXO) utilizing dual mode frequencies of an SC-cut resonator as the means of temperature compensation. The first phase of the contract program included a study and investigation of the behavior and inter-relationship of the dual B-mode and C-mode frequencies of various SC-cut resonators under varying temperature conditions (with data to be taken at temperatures

<sup>(4)</sup> J. Kusters, M. Fischer, and J. Leach, "Dual Mode Operation of Temperature and Stress Compensation Crystals", Proc. 32nd Annual Symposium on Frequency Control, pp 389-397, 1978

<sup>(5)</sup> U.S. Patent 4,079,280; "Quartz Resonator Cut to Compensate for Static and Dynamic Thermal Transients", J. Kusters, J. Leach, M. Fischer: March 14, 1978

ranging from -55°C to +100°C), together with the delivery of two ECXO test oscillator units. This research program was performed during the period 1 June 1981 - June 1982. Subsequently, under an optional task statement, the contract was extended to include further investigation into hysteresis, re-traceability, stability, and aging characteristics of dual mode operation under controlled temperature cycling and intermittent operation. This portion of the contract work covers the period 1 January 1983 - 31 December 1983.

#### 1.2 ACKNOWLEDGEMENT

This work was performed under the supervision of Dr. O.J. Baltzer, Principal Investigator. Mr. Charles S. Stone, Brightline Corporation, under a consulting agreement with Tracor, Inc., had major technical responsibility throughout the project, including the design of the instrumentation system used in the investigation and the design, subsequent modification, calibration and testing of the ECXO units. Charles Baltzer developed the digital portions of the ECXO design, including the preparation of the compensation look-up table and syntonization algorithms. Robert L. Nelson was responsible for a study exploring the feasibility of the hardware implementation of an ECXO system, as an alternative to a microprocessor implementation. Clement Ip undertook a large share of the environmental testing and measurement of the B-mode and C-mode frequency characteristics of the various SC-cut quartz resonators tested; he also participated in the software development of

various data logging and data analyses programs. We also wish to acknowledge that several of the SC-cut resonators used in this project were kindly supplied by Dr. John Vig, ERADCOM, Ft. Monmouth, N.J. The authors are also deeply indepted to Mr. William F. Donnell, Tracor Program Manager, and Mr. Alfred Kahan, RADC/ESE, for their many helpful discussions and their assistance and constant support throughout the contract program.

# SECTION 2

# DISCUSSION OF THE ECXO CONCEPT

# 2.1 ADVANTAGES OF THE ECXO APPROACH

Virtually all of the crystal oscillators currently used in communication applications attempt to achieve accuracy in time/frequency by means of internal frequency control ('tuning') of the oscillator itself. In the case of oven-controlled crystal oscillators (CCXO), the quartz resonator is maintained at a constant temperature close to its frequency turning point; consequently, only vernier frequency tuning is then required. However, in the case of ovenless temperature-compensated crystal oscillators (TCXO) utilizing internal frequency control, the problem is more severe. The quartz crystal is deliberately "pulled" off of its natural frequency resonance, often by an extreme amount, to compensate for the temperature-dependent characteristics of the quartz crystal. The required 'tunability' is only obtained at the expense of instability and loss of accuracy. As a result of this intrinsic limitation, even though much research and development effort has been given to the conventional TCXO approach for more than two decades, currently available TCXO units fall far short of providing reliable frequency accuracy over any extended temperature range or interval of time.

The external compensated crystal oscillator (ECXO) approach, in contrast to the conventional TCXO, retains the intrinsic stability and accuracy inherent in quartz crystal itself. This

is achieved by utilizing external adjustment of the output signal rather than internal 'pulling' of the quartz crystal element.

Tracor has applied this principle (external compensation of a crystal oscillator, under microprocessor control) for many years in various models of the Tracor airborne Omega navigation system. An oven controlled precision OCXO is used as the clock for the computer and as the reference phase source for measurement of all received signal phases. The OCXO accuracy is, however, orders of magnitude away from that needed for OMEGA/VLF navigation. To compensate for oscillator inaccuracy, the microcomputer makes repeated measurements of the clock offset, based on all of the received-signal phases. These measurements are used both to correct the phase ('time') of the clock and to determine its phase-rate ('frequency drift') error in a second-order tracking loop. The corrections thus obtained are not applied directly to the oscillator, which is allowed to run freely; rather, they are employed entirely within the computer to produce the effect, external to the oscillator, of much greater accuracy. The present project differs in part from the CMEGA/VLF compensated OCXO oscillator in that it involves direct temperature compensation of an ovenless oscillator, operating over a wide temperature range.

The current feasibility of high accuracy, low power, ovenless ECXO is largely made possible by technological advances and development in several distinct areas:

1. Development and availability of new quartz resonators (e.g.,

SC-cut) with radically improved performance features;

- 2. Recognition of the B-mode frequency (in SC-cut crystals) as a highly precise, digital thermal sensor;
- 3. Recognition of the external compensation approach as the proper means of achieving improved time/frequency accuracy.
- 4. Significant advances in microprocessor technology.

The properties and advantages of the doubly-rotated SC-cut quartz crystal are well known and have been widely described in various papers in recent years. Only a brief summary need be given here. The major advantages cited for C-mode operation with SC-cut crystals, relative to an AT-cut crystal, include: improved frequency-temperature characteristics under both static and dynamic conditions; insensitivity to thermal transients; reduced sensitivity to acceleration (attitude, shock, and vibration); and freedom from activity dips.

One potential problem with the SC-cut crystal is the B-mode of oscillation, some 10% higher in frequency than the C-mode. In most oscillator applications, the B-mode is unwanted and suppressed--either by greater oscillator circuit complexity or by use of a crystal design which increases the resistance of the B-mode of oscillation considerably above that of the desired C-mode. In the ECXO application, however, the B-mode frequency is purposefully used as a precise means of measuring crystal temperature directly.

Other disadvantages cited for the SC-cut--in non-ECXO applications--are the manufacturing difficulties of controlling

the temperature turning point, inflection temperature, and the finishing frequency tolerance to the required accuracy. Another disadvantage, in non-ECXO applications, is the "stiffness" of SC-cut crystals, particularly of 3rd or 5th overtone types; it is difficult to trim these resonators by the conventional capacitor tuning adjustment method. However, the compensation techniques used within the ECXO provides a versatile means of frequency adjustment, even for SC-cut crystals which have been finished to very loose manufacturing tolerances. The finished frequency and the turning point temperature of any ECXO crystal can vary considerably from the nominal design values without any degradation in accuracy of performance (for example, an ECXO with an oscillator frequency offset as large as  $\pm 1 \times 10^{-3}$  can be adjusted to within  $\pm 1 \times 10^{-9}$  of the correct clock frequency--a compensation factor that is utterly unattainable with analog compensation methods).

With the externally compensated crystal oscillator approach, the oscillator can be expressly designed for maximum performance (highest Q, highest stability, etc.) without any requirement for the inclusion of a varactor or other element that might affect ultimate stability.

The ECXO concept need not be restricted to temperature compensation (although this, generally will be a major objective). The compensation can be extended to other measureable or predictable parameters. For example, the quartz crystal need not be manufactured to a tight turnover temperature

or finishing tolerance (an advantage if SC-cut overtone crystals are to be manufactured at a reasonable cost). Any fixed frequency offset, either initially or observed at a later calibration date, can be readily removed.

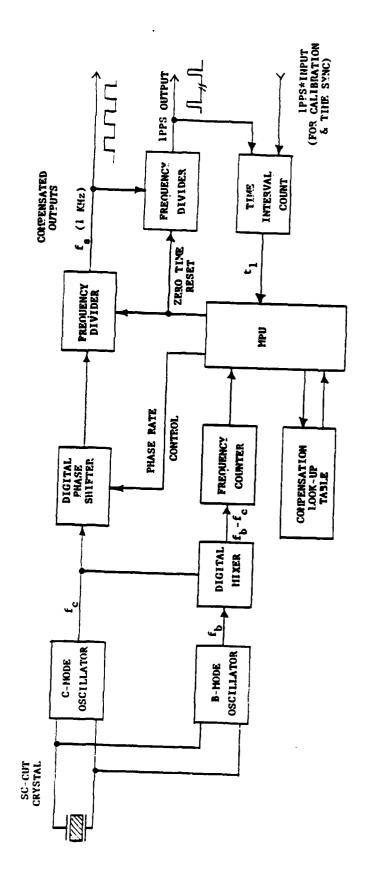
Finally, the long-term frequency drift (aging) observed in high stability quartz resonators frequently proceeds at a nearly uniform, systematic rate. This leads to the possibility that a microprocessor ECXO can be programmed or calibrated to provide some measure of compensation for systematic aging.

The remarkable and continuing advances in solid state technology and microcomputer components opens up the feasibility and practicality of a moderately sophisticated ovenless ECXO system capable of reliable, accurate operation at very low power (say, less than 20 milliwatt). The power dissipation in CMOS integrated circuits is the sum of the quiescent (d.c.) and the dynamic (a.c.) components. The quiescent component becomes significant only under conditions of high temperature and high voltage; for example, the quiescent dissipation of a complex MSI device such as the RCA CD4516B Presettable Up/Down Counter approaches 1 milliwatt at +85°C with a supply voltage of +5Vdc. The dynamic dissipation, on the other hand, of this counter has a typical value of roughly 10 milliwatt at a clock frequency of 5MHz for the same +5Vdc supply.

The dynamic power in CMOS circuits is roughly proportional to the product  $f \times V^2$ , where f is the input frequency and V is the supply voltage. Thus, a 5:1 reduction in power dissipation

can be achieved if a digital counter or CMOS microprocessor is operated at 1 MHz instead of 5 MHz. Operation at reduced supply voltages also lowers power consumption, and, consequently, deserves consideration. The higher power consumption will undoubtedly occur at the input digital counter/frequency divider stage in the C-mode channel; the B-mode frequency channel can be heterodyned to the lower difference frequency (B-C) before any digital frequency division process need occur, thereby lowering its power requirements. Once initial frequency division (say, by a factor of 16 or more) has been achieved, the remaining digital circuits, including the microprocessor and PRCM memory, will not add significantly to the power budget.

2.2 Externally Compensated Crystal Oscillator (ECXO) Development The initial Tracor ECXO is shown in simplied block diagram in Figure 2-1. This unit used an SC-cut crystal operating at dual C-mode (10.23 MHz; 3rd overtone) and B-mode frequencies. The C-mode frequency is passed through a digital phase shifter (a programmable frequency divider which is controlled by the MPU microprocessor) and is further divided to provide time-corrected 1 pps and 1 kHz output signals. The temperature sensitive E-mode frequency,  $f_b$ , is down converted to the difference frequency ( $f_b - f_c$ ) by the digital mixer ( $f_b - f_c$ ). The measurement of ( $f_b - f_c$ ), in place of  $f_b$ , can be performed with a simpler lower frequency counter, thereby enabling a saving in power consumption. The time base for the frequency counter is derived by division from the time-corrected C-mode frequency. The measured value of



BLOCK DIAGRAM: TRACOR EXTERNALLY COMPENSATED CRYSTAL OSCILLATOR (ECXO)

FIGURE 2-1

 $(f_b-f_c)$  is used by the microprocessor to adjust the C-mode frequency in accordance with a previously established calibration curve.

The time/frequency adjustment is implemented by adding or deleting counts in the digital phase shifter. The size of each step is roughly  $\pm 2$  microseconds (the basic 10.23 MHz oscillator frequency is divided down to 501.2 kHz because of frequency limitations of the microprocessor (MPU) used in the unit). A  $\pm 2$  microsecond correction can be made each millisecond; accordingly, the system is able to handle frequency offsets as large as  $\pm 2$  x  $\pm 10^{-3}$ .

It must be noted that a digital ECXO of this simple type produces discrete phase steps, rather than a continuous phase rate, in the output waveforms. A  $\pm 2$  microsecond quantization error will be negligible in most real time/clock applications. It will affect, however, the required length of "calibration" time to achieve a specified clock frequency accuracy (e.g., approximately 100 sec. of time is required for syntonization to  $\pm 2 \times 10^{-8}$ , etc.).

The Tracor ECXO includes microprocessor hardware and software features to facilitate automatic synchronization and frequency re-calibration of the system from an external 1 Hz reference signal pulse. It is merely necessary to connect a 1 pps time standard to the unit. The microprocessor accepts an incoming signal as a "valid" calibration source only if it meets certain criteria with respect to amplitude, frequency tolerance,

and absence of jitter, thereby avoiding any possibility that the unit will attempt to synchronize on a noisy or incorrect signal. The software is designed such that the frequency calibration accuracy continues to be refined throughout the time interval that the calibration source is connected to the unit.

The breadboard ECXO uses the Motorola 6802 CPU microprocessor (with 64 bytes of internal RAM), in combination with a Motorola 6840 timer chip, for the major control, logic, and counter/timing functions. The instruction program and the compensation look-up table values are stored in a standard EPROM memory (a 2716 NMOS 2048 x 8-bit UV eraseable PROM). Several low power Schottky integrated circuits (e.g., 74LS74, 74LS390, etc.) are also used for auxiliary gating and buffer amplifier purposes.

The required temperature compensation pattern for each SC-cut crystal was individually determined by means of calibration in a temperature chamber. To collect the raw data from which the look-up table was prepared, simultaneous readings of C-mode and B-mode (or, alternatively,  $f_b$ - $f_c$ ) frequencies were taken as the temperature of the environmental test chamber was cycled over the full temperature range (the exact temperature need not be known since temperature only enters parametrically into the  $f_b$ - $f_c$  frequency ratio). For the case of the two ECXC units, it was found that the raw data for each SC crystal approximated a cubic equation. A general purpose mini-computer was used for verifying this and for determining the coefficients of the resultant cubic equation. The individual compensation

values to be programmed into the PROM look-up table were then determined, again with a general purpose computer, so as to properly match the cubic equation at selected intervals along the temperature range.

The compensation algorithm within ECXO memory provides a linear interpolation procedure between the discrete points stored in the table. The table incorporates some 200 points, each 16 bits in length.

Computer simulation of the compensation algorithm was used to demonstrate that the total compensation program would operate satisfactorily, without introducing any significant systematic or random error in either clock frequency or timing over extended intervals. These computer simulation runs demonstrated that the compensation algorithm in itself would introduce considerably less than 1 millisecond time error over a 24-hour operating interval in a typical temperature environment.

Initial testing of the two demo units under fluctuating room ambient conditions indicated that a timing accuracy of better than  $\pm 1$  millisecond could generally be maintained for 1-3 days after time sychronization and frequency re-calibration. Re-calibration was performed by means of a laboratory standard 1 pps signal having an accuracy of  $\pm 1 \times 10^{-10}$  or better. In some instances a systematic drift of several parts in  $10^9$  was observed throughout the test period; in other runs the time error appeared to follow a random walk pattern, with the apparent frequency fluctuating over a range of approximately  $\pm 2 \times 10^{-8}$  during a

several-hour period.

Subsequent environmental chamber testing of one of the units several months later showed, however, an inexplicable frequency offset of perhaps 1 x 10<sup>-7</sup>. The question then arose whether the deviation was due to an intrinsic change in the B-mode or C-mode resonant frequency of the quartz crystal or to a change in some circuit component. To resolve this crucial question it was decided that basic measurements of the B-mode and C-mode frequency characteristics of SC-cut resonators were prerequisite to the ECXO program.

#### SECTION 3

# INVESTIGATION OF DUAL MODE (B & C) FREQUENCY CHARACTERISTICS OF SC-CUT CRYSTALS

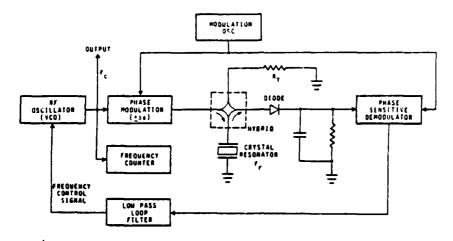
#### 3.1 INTRODUCTION

The early ECXO used a modification of the familiar Butler oscillator circuit for simultaneous excitation of the B-mode and C-mode frequencies. There is an inherent problem in any active feedback type of oscillator that attempts to generate two independent frequencies from a dual mode crystal. Frequency selective networks must be employed to separate the modes and to prevent undesirable interaction between the individual frequency modes. The electronic parameters of the components used in the frequency-selective feedback loops will show some residual drift with time and changes in environmental conditions. Consequently, the long-term stability and aging characteristics of any conventional oscillator used in a dual B-mode and C-mode resonator application can be questioned.

# 3.2 THE PHASE MODULATED FREQUENCY DOMAIN REFLECTOMETER

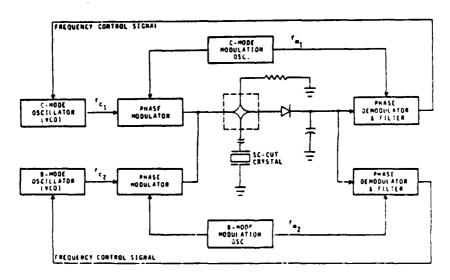
A review was therefore made of alternative methods for laboratory investigation of the B-mode and C-mode frequencies of precision SC-cut resonators. As a goal, such instrumentation should be able to provide a significantly higher level of measurement precision (say, by a factor 10 or more) than that required in an operational ECXO. An instrumentation system employing a unique phase modulated, frequency-lock reflectometer was selected; Figure 3-1 shows the basic concept. The crystal is used here as a passive resonator in a frequency-lock servo

F.L. Walls and S.R. Stein, "A Frequency - lock System for Improved Quartz Crystal Oscillator Performance," IEEE Trans. on Instrumentation and Measurement, Vol. IM-27, pp. 249-252. Sept. 1978.



PMASE-MODULATED REFLECTORETER SYSTEM (FOR FREQUENCY-LOCKING AM OSCILLATOR TO A PASSIVE QUARTE RESONATOR).

FIGURE 3-1



DUAL HODE FREQUENCY-DOMAIN REF.ECTOMETER

FIGURE 3-2

oscillator system. The advantages of this system include: (1) the crystal resonator may be remotely located (e.g., in an environmental test chamber) away from the rest of the instrumentation; (2) significantly improved immunity to component parameter values; (3) the potential for almost complete freedom from interaction between the C-mode and B-mode portions of the ECXO; (4) the ability to achieve accurate, repeatable crystal measurements and a quality of temperature compensation that is limited only by uncertainties intrinsic to the resonator; and (5) the ability to maintain a specified, constant level of independent excitation for C-mode and B-mode frequencies without a requirement for AGC.

An external, independent voltage-controlled oscillator generates a carrier frequency,  $\mathbf{f}_{\mathbf{C}}$ , in the vicinity of the crystal resonant frequency. A small phase modulation,  $\pm \Delta \mathbf{C}$ , is applied, and the resultant phase modulated signal is used to interrogate the crystal resonator. The reflected signal from the resonator, after passing through an isolation amplifier, is amplitude detected by a diode and capacitor filter. An amplitude modulation, at the modulation oscillator frequency, is observed in the detector output whenever the carrier frequency differs from the resonant frequency,  $\mathbf{f}_{\mathbf{r}}$ , of the quartz resonator. The sense and magnitude of this detected amplitude modulation depends upon the frequency deviation of the voltage-controlled oscillator from the center of crystal resonance.

A phase sensitive detector is used to provide a d-c error

signal proportional to the frequency offset of the oscillator.

This error signal, after suitable low pass filtering, is used to servo control the oscillator, thereby frequency-locking the oscillator to the crystal resonant frequency.

It will noted that Figure 3-1 utilizes a directional coupler (or four-port hybrid transformer) for coupling the phase modulated input signal to the quartz resonator. The use of the hybrid transformer enables good isolation to be achieved between the input to the crystal and its reflected output signal.

Dual mode operation from a single resonator can be obtained by utilizing separate frequency-lock oscillators for the individual C-mode and B-mode frequencies (Figure 3-2).

Interaction between the two modes can be eliminated by using separate, non-related modulation frequencies for the phase modulation/demodulation processing, together with good low pass filtering in the servo control loop.

A better understanding of the operating principles of the modulated system can perhaps be otained from the vector diagrams of Figure 3-3.  $R_1$  and  $R_2$  represent the successive vectors associated with the incident signal as the result of the square wave phase modulation process;  $S_1$ ,  $S_2$  and C represent the equivalent sidebands and carrier components for this phase modulated signal. The corresponding reflected components are shown on the right. The crystal resonator unit appears as a very high impedance (highly reactive) for all frequency components even slightly removed from resonance; accordingly, the reflected

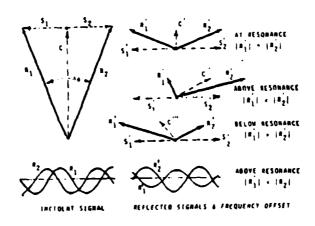


FIGURE 3-3

sideband components, S'<sub>1</sub> and S'<sub>2</sub>, are virtually equal to the incident components, S<sub>1</sub> and S<sub>2</sub>, and maintain the same 180° relationship to each other. It is the carrier component that changes in magnitude and phase as the crystal resonant frequency is approached. At resonance, there is likely to be a residual reflected component, C' (as the result of any nominal mismatch between the ESR of the crystal and the hybrid termination resistance R<sub>y</sub>). However, this C' component (at resonance) is orthogonal to the sideband component vectors so that the resultant vectors, R'<sub>1</sub> and R'<sub>2</sub>, are equal in magnitude. Away from resonance, the reflected carrier component (C'' or C''') increases in magnitude and undergoes a large phase shift; accordingly, the two vectors, R'<sub>1</sub> and R'<sub>2</sub>, are no longer equal in magnitude and, consequently, an error signal is generated in the synchronous demodulation process.

The length of the interconnecting cable between the quartz resonator and the balance of the instrumentation does not materially influence the measured resonance frequency if the hybrid bridge is properly terminated to match the cable impedance. An ideal, non-dispersive cable would affect the carrier and sideband frequency components in an identical manner, thereby producing no change in the relative magnitude or phase of the detected vector components. Furthermore, for moderate lengths of commonly available transmission cables, the dispersion effect is quite small and can generally be neglected. This has been confirmed in simple tests wherein an additional 50 feet of

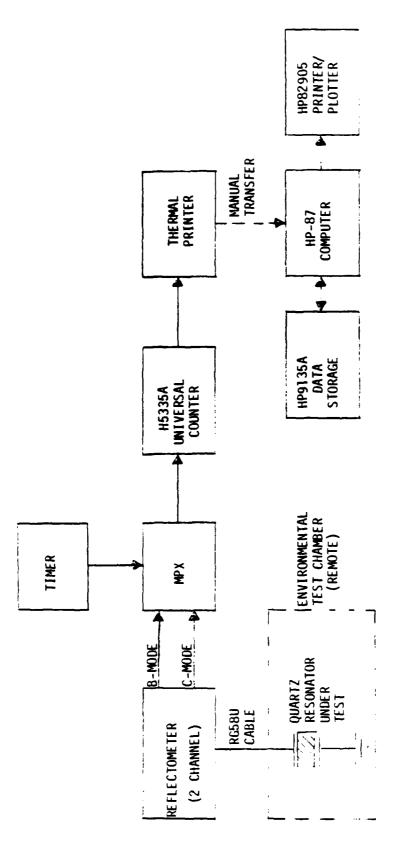
RG-58U cable has been inserted between the resonator and the reflectometer bridge; without using extreme care in adjusting the hybrid termination, a frequency deviation of less than  $5 \times 10^{-9}$  was observed.

# 3.3 DATA ACQUISITION AND ANALYSIS INSTRUMENTATION

Figure 3-4 shows the measurement system used during the early phases of the project. A brassboard dual channel reflectometer enabled the measurement of the B-mode and C-mode resonant frequencies of the SC-cut quartz crystal to a precision of  $\pm 2 \times 10^{-9}$ . The crystal resonator, together with the hybrid transformer, was remotely located within the environmental test chamber. Standard RG-58U coaxial cable, approximately 5 meters in length, linked the crystal resonator to the reflectometer.

A timer, with a total cycle time adjustment between 1-10 minutes, controlled the multiplexer (MPX). During each cycle the two R-F frequencies were sequentially switched in the pattern: E (for 1 second duration); C (for 3 seconds); and B again (1 second). The first and second B-frequency values were averaged together to provide an "interpolated" B-mode reading matching the time frame of the intermediate C-reading. Simultaneous E and C-mode readings with two counters would have obviated this requirement for a multiplexer and dual B-mode readings.

The HP-5335A is a highly versatile counter that provides a precision and resolution of  $\pm$  2 x  $10^{-9}$  for a gating interval of 1 second. The 3-second interval for the more critical C-mode



EARLY INSTRUMENTATION SYSTEM FIGURE 3-4

frequency enables a counter measurement precision in excess of 1  $\times$  10<sup>-9</sup>. All data throughout the project were taken relative to a laboratory reference standard having an accuracy of  $\pm 2 \times 10^{-9}$  or better (using periodic calibrations based on Loran C signal reception).

In the early work the individual frequency readings were simply outputted from the counter onto a paper tape printer. After completion of a full temperature run, the tape data were visually read and manually keyed into the HP-87 computer for permanent storage and analysis.

Discrete frequency-temperature data of this type can be analyzed in various ways. The approach which appears to be most useful involves determination of the frequency deviation of the data from an assumed power series polynomial of the Nth degree. It is known that the frequency-temperature dependency of the C-mode frequency can be reasonably approximated with a cubic equation. However, with the powerful computer techniques available today, it is readily possible to utilize a higher degree polynomial expansion, if this will provide more useful interpretation of the data.

All of the data in the subsequent section are presented in terms of the residual frequency deviation of the individual data points from an "ideal" or predicted power series polynomial of the form

$$P = A_0 + A_1 x + A_2 x^2 + \cdots + A_N x^N$$
 (Eq. 1)  
where P is the predicted frequency and x is a

temperature-dependent frequency variable (e.g., the B-C frequency difference) that forms the basis for the temperature compensation technique. The individual polynomial coefficients in the series can be computed by employing standard regression techniques on a selected set of C-mode and (B-C) frequency data pairs. (The software program "REGR/2107' in Appendix B of this Final Report utilizes this capability).

It might be noted that deriving a high order polynomial (e.g., N=5 or higher) from a large number of data pairs requires considerable computer time and, in addition, places some burden on computer accuracy if the magnitude of the variable, x, is too large. Consequently, the B-C frequency value is generally offset and reduced by an arbitrary constant in establishing the variable x used in Equation 1.

Figure 3-5 shows the improved automatic data logging system employed during the later stages of the project. This configuration utilizes the HP-IB (IEEE-488) Interface Bus for system control and transfer of data. The HP-87 computer forms the "controller" for the system and, in addition, can be used for preliminary plotting and analysis of the raw data on a real-time basis. For this purpose it is merely necessary that the operator insert an appropriate set of polynomial coefficients for the particular crystal(s) under test. The computer will then print out and graphically plot, on real-time basis throughout each temperature run, the frequency deviation of the successive C-mode frequency values from the predicted polynomial. The program

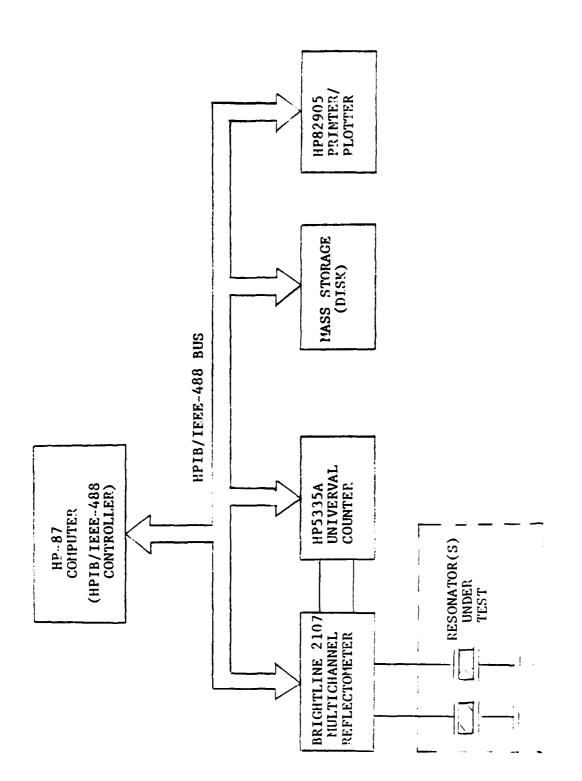


FIGURE 3-5. DATA LOGGING/INSTRUMENTATION SYSTEM

listing, "DATA/PLOT", in Appendix C gives the actual program used for (a) controlling the reflectometer and counter gating; (b) storing the raw data sets on disk; (c) operator inputting of the polynomial coeifficients; (d) hard copy printout of the individual "raw" frequency data and time; (e) printout of the frequency deviation, & f/f, of the C-mode frequency from its corresponding predicted value based on the assumed polynomial approximation; (f) a plot of these same frequency deviation values on the CRT terminal; and (g) on command, a "dump" of the resultant CRT graphics display onto the printer/plotter.

### 3.4 TEST RESULTS

The present investigation into the behavior and interrelationship of the dual mode frequency characteristics of SC-cut quartz resonators has demonstrated the tremendous potential of the dual mode ECXO in low power, ovenless clock driver and timing applications. All results obtained to date, although limited to a relatively small sample of SC-cut crystals from several suppliers, indicate an attainable frequency accuracy of several parts in 10<sup>8</sup> over the full military temperature range of -55°C to +85°C (corresponding to an equivalent clock accuracy of several milliseconds/day or better). This approaches a 100-fold improvement over that obtainable in practice with a varactor-type TCXO over the same extreme temperature range. It must be noted, of course, that the any accuracy value given here is based solely on the intrinsic stability of the dual mode quartz resonator that forms the nucleus of the ECXC; however,

with further research, it should be possible to develop suitable oscillator and associated microprocessor circuits that do not materially degrade the intrinsic resonator performance.

A total of several hundred thousand data points, covering more than fifty separate environmental test chamber runs, were probably logged during this investigation. Many runs, particularly during the early months of the work program, were duplicated to ensure that the instrumentation was working properly and that valid results were being obtained. Accordingly, only a small, representative sample of the more recent test data, together with a review of the significant conclusions that can be drawn from the data, will be represented here.

Table 3-1 illustrates the format used for print-out of the raw data, together with interim processing of these data, on a real-time basis. The first 40 lines of a temperature run (with the full run covering a 60 hour cycle) are reproduced here. Each set of data logging includes two sequential pairs of dual-mode frequencies in the sequence  $\mathbf{E_i}$ ,  $\mathbf{C_i}$ ,  $\mathbf{B_i}$ ,  $\mathbf{C_i}$ . The values in the column TMODE1 are the average of the  $\mathbf{B_i}$  and  $\mathbf{B_i}$  readings; the column TMODE shows the differential between these two readings. The column CMODE gives the CMODE readings; the column CMODE shows the difference between successive rows of CMODE values (here separated by a sampling time interval of approximately 51 seconds, as evident by inspection of the TIME column). TAPPROX approximates the apparent temperature of the quartz resonator

CRYSTAL TYPE: COLORADO CRYSTAL

SC-CUT

S/N 1

SMHZ SRD OVERTONE

FREQUENCY REFERENCE: 2106-9

CRYSTAL ORIENTATION: +X

RUN STARTED: 27 JUNE 1983 10:50AM

FRED STD ACCURACY: 3110E-9

C-MODE: 4.5

INCIDENT CRYSTAL POWER (MICROWATTS): 8-MODE: 1.5 INITIAL OVEN TEMP: 24 INITIAL T-MODE FREQ: 5478136 INITAL F-MODE FREQ: 4499972.1

THAX: 85 THIN: -55 TEMPERATURE PROFILE: 1 DEGREE C/12 HIN (NOHINAL): A SLOW RATE FOR STATIC HYSTERESIS STUDY 

A(0) -- 71.781881

A(1)= .0185502

A(2)=-6.0170229E-7 A(3)=-8.360294149E-11

A(4) ==5. 962305177E=16

A(5) = 1.770633048E-20 A(6) = 0

THE FOLLOWING PROGRAM INPUTS BSC MODE FREQUENCIES FROM COUNTER HPSSSA AND STORES DATA ON THE FLOPPY DISC. A DATA FILE CALLED EXTALDATAS IS CREATED.

NO.	THODE	-THODE	CHODE	~CHODE	TAPPROX	TIME	OF/F DEV X KZ
1 :	3478134.05	57	4999972.151 .		+24.01	37462	*
2 5	5478135.39	68	4 <del>9999</del> 72.139	012	+24.00	39512	+1.52E-08 +8.164
3 9	5478134.99	80	4 <del>9999</del> 72.124	015	+23.99	37543	+1.51E-08 +6.145
4 :	5476158.83	87	4 <del>9999</del> 72.108	016	+23.98	37614	+1.54 <b>E-</b> 08 <b>+8</b> .167
5 5	5478140.92	-1.03	4999972.089	019	+23.96	39665	+1.5 <b>4E-08</b> +8.169
	5478145.32	-1.15	4 <del>9999</del> 72.067	022	+23.94	39716	+1.55E-08 +6.172
	478145. 75		4999972.043	OZ4	+23.92	39768	+1.55E-08 +6.175
= = =	3478148.71		4999972.019	024	+23.90	37616	+1.57E-08 +8.177
	3478151.52		4999971.992	027	+23.98	37868	+1.54E-08 +8.180
	478155.22		4999971.958	034	+23.85	39919	+1.60E-08 +8.184
	478157.88		4999971.915	043	+23.82	39970	+1.41E-08 +8.189
	3478164.93		4999971.848	047	+23.78	40021	+1.40E-08 +8.174
	478170.04		4999971.822	046	+23.75	40073	+1.61E-08 +8.199
	3478173.34		4999971.772	050	+23.71	40123	+1.62E-08 +8.205
	478181.49	-	4999971.718	054	+23.66	40174	+1.49E-08 +0.211
	3478188.07		4999971.657	061	+23.41	40225	+1.70E-08 +8.218
	3478194.74		4999771.596	061	+23.56	40276	+1.725-08 +8.225
	3478201.41		4999971.532	064	+23.51	40326	
	3478208.85		4999971.463	049	+23.46	40377	+1.746-08 +8.239
	2478217.08		4999971.386	077	+23.40	40429	+1.79E-08 +8.248
	5478222.58		4999971.303	083	+23.34	40479	+1.746-08 -8.256
== .	478233.99		4999971.226	077	+23.28	40530	+1.80E-06 -8.265
	3478242.53	_	4999971.145	081	+23.21	40581	+1.84E-06 +8.270
	547 <b>8</b> 251.64 547 <b>8</b> 260.93		4999971.058	087	+23.15	40632	+1.87E-08 +8.193
			4999970.968	090	+23.08	40683	+1.875-08 +8.292
	5478270.17 5478279.28		4999970.881	087	+23.01	40735	+1.91E-08 +8.301
	347 <b>828</b> 9.40		4999970.790	091	+22.95	40785	+1.91E-08 +8.311
	3478300.09		4 <b>9999</b> 70.690	:00 :05		40836	+1.946-08 +8.321
	3478310.70	• • •	4999970.482	103	+22.79 +22.72	40 <b>886</b> 40 <b>93</b> 7	+1.96E-08 +8.332 +2.00E-08 +6.343
	5478321.01		4999970.381	101	+22,64	40988	+1.02E-08 +8.323
	3478531.44		4999970, 275	101	+22.57	41040	+2.02E-08 +8.364
	2478342.12		499997C.168	107	+22.49	41090	+2.085-08 -8.374
	3478332.76		4999970.061	107	+22.41	41141	+2.106-09 +8.385
	5478562.99		4999969.960	101	+22.34	41192	+2.14E-08 +8.195
	5478373.02		4999969.853	107	+22.27	41243	+2.13E-08 -8.40b
	5478383.93		4999969,742	111	+22.19	41294	+2.20E-08 +8.417
-	2478392.14		4999949.625	117	+22.10	41545	+2.20E-08 +6.428
	3478406.11		4999969.513	112	+22.03	41396	+2.25E-08 +8.473
-	3478416.63		4999969.401	112	+21.95	41446	+2.24E-08 +6.450

TYPICAL PRINTOUT OF B & C-MODE DATA ON REAL-TIME BASIS

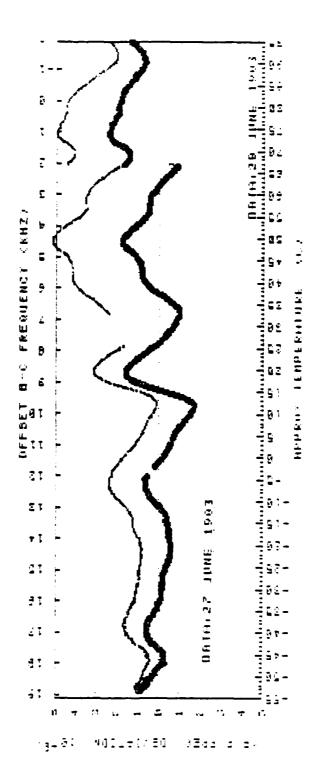
TABLE 3-1

under test (based upon an assumed linear relationship between B-mode frequency and temperature of  $-138 \, \mathrm{Hz/^{O}C}$  over the full operating range).

The tabulated frequency deviation values, A F/F, are shown relative to a 5th degree polynomial. The polynomial coefficients, once derived from an initial "calibration" run, can be utilized in all subsequent runs to measure hysteresis, aging effects, etc. The last column shows the offset B-C frequency value (in kHz) that is used as the independent variable in the polynomial frequency correction expression.

Certain initial information must be provided by the operation prior to a new run (e.g., type of crystal, incident crystal power, planned temperature profile, etc.). This ancillary information, as shown, is also stored on each disk and is used to aid in subsequent identification and analysis.

In addition to the hard-copy digital printout, the computer terminal provides a real-time, ongoing display of the frequency deviation of the individual readings as they are accumulated. This visual display can then be "dumped" onto a printer/plotter upon command. Such a plot is shown in Figure 3-6. This represents a total of 4,000 readings, taken over a 60 hour period, at oven intervals of less than 0.1°C. The lighter, upper trace indicates data taken during the decreasing temperature portion of the cycle; the heavier trace (formed by the broad sympbol 'o', rather than a simple '.', indicates increasing crystal temperature.



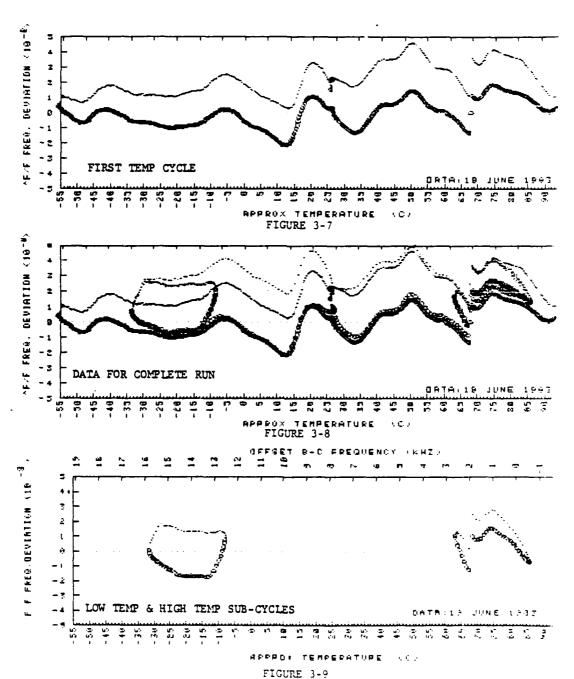
PLOT OF FREQUENCY DEVIATION FOR SC-CUT CRYSTAL (COLORADO CRYSTAL CO. S/N 1) DURING SLOW TERMPERATURE CYCLING (1<sup>O</sup>C/12 MINUTE). UPPER TRACE: DATA DURING DECREASING TEMPERATURE; LOWER TRACE: INCREASING TEMPERATURE

FIGURE 3.6

Several significant features can be noted in these plots. Even at the relatively low temperature rate of ±5°/hour, there is a clear-cut displacement between the increasing and decreasing temperature curves: roughly, a frequency differential of ±1.5 x 10<sup>-8</sup> is seen between the negative rate and positive rate sections. There is also an observable activity dip in the B-mode; for this particular crystal, the transition occurs at approximately +68°C. Similar B-mode activity dips have been observed in the other crystals that have been tested. In some cases, it has not been possible to maintain satisfactory operation over the entire -55°C to +85°C range; however, for this crystal (Colorado Crystal Co; S/N 1) the dip shows up simply as an abrupt transition, with a frequency deviation step of less than 3 x 10<sup>-8</sup> in the apparent C-mode compensation term.

Figures 3-7 and 3-8 show comparable performance at higher oven rates. Figure 3-7 slows one complete temperature cycle at an oven rate of  $\pm 1^{\circ}$ C/3 minute (roughly, quadruple the rate used for the Figure 3-6 run). However, there is only a moderate increase in the separation of the upward and downward temperature regions.

Figure 3-8 shows the cluttered "real time" plot that results when all data from a complex temperature run are displayed on a single plot. In this instance, the quartz resonator was cycled over two separate low temperature and high temperature sub-regions as well as an additional two cycles over the full -55°C to +95°C range. The computer program is set up so that, in



100KE 3-9

subsequent analysis, selected segments of the stored raw data can be retrieved and analyzed. This capability is shown in Figure 3-9. The left-hand hysteresis loop shows an intermediate segment in which the oven temperature was increased and then decreased so that the crystal, while at a temperature of  $-32^{\circ}$ C from a previous temperature cycle, was raised to roughly  $-5^{\circ}$ C and then returned to  $-32^{\circ}$ C (over a time interval of 1 hour). The right-hand pattern shows similar resonator behavior in the high temperature region between  $+60^{\circ}$ C and  $+85^{\circ}$ C: the upper dotted trace shows the frequency deviation during the temperature decrease, and the points with the square symbol show data taken during increasing temperatures. The step transition due to the activity dip is clearly evident in each trace.

The most striking feature of the dual mode frequency behavior is the high stability and repeatability of the frequency deviation patern for successive runs under similar test conditions. There is also clear evidence of a repeatable hysteresis or thermal shock effect during temperature cycling. The test results indicate that simple temperature compensation (e.g., without additional compensation for the rate of temperature change) cannot yield the highest accuracy. For example, to achieve 1 x 10<sup>-8</sup> accuracy it will be necessary that some form of thermal rate compensation be employed. If the functional relationship can be determined, either on an empirical or physical basis, any required additional computational task can be readily accomplished by simple microprocessor means.

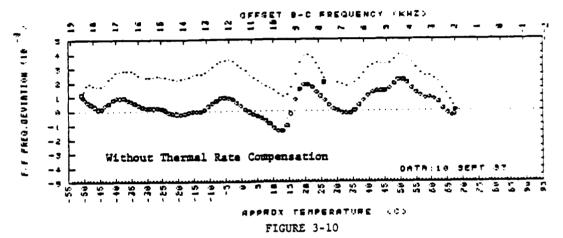
For static temperature compensation, the computed frequency compensation term, P(TEMP), a function of temperature, is assumed to approximate a polynomial power expression of the form

 $P(TEMP) = A_0 + A_1x + A_2x^2 + \cdots + A_Nx^N.$  (Eq. 1A)

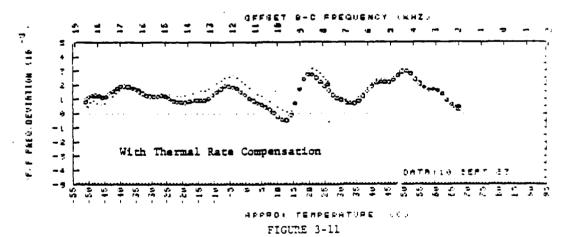
Thermal transient compensation can be included by modifying this expression to form a new compensation factor,

 $P'(\text{TEMP}) = P(\text{TEMP}) + K \left[1 + K(2) * (T_2 - 25)\right] \left[\frac{(T_2 - T_1)}{(t_2 - t_1)}\right] \quad (\text{Eq. 2})$  where K and K(2) are thermal rate coefficients and  $(T_2 - T_1)$  represents the change in crystal temperature over the time interval  $(t_2 - t_1)$ . The K factor introduces a frequency compensation value that is directly proportional to the thermal rate at any point in the temperature cycle; the K(2) factor, on the other hand, introduces a secondary correction that also controls the rate compensation as a function of crystal temperature (thereby permitting differential adjustment of the rate compensation over the low temperature and high temperature regions).

A limited number of data analysis runs were made to determine a pair of suitable values for both the K and the K(2) coefficients. For example, Figure 3-10 shows the frequency deviation relative to a derived fifth order frequency-temperature polynomial for a dual mode SC-cut crystal without rate compensation. The upper trace (small dots) represents data taken during decreasing temperatures; the lower trace (small open squares) indicates corresponding points for increasing temperatures. The environmental chamber was programmed to give a



NOTE: WITH TEMP RATE COMPENSATION: K=-1\*10^-6:K(2)=-0.005 (FIRST TEMP CYCLE)



temperature ramp at an approximate rate of  $\pm 0.5^{\circ}$ C per minute. A frequency deviation differential in excess of 2 x  $10^{-8}$  is obvious between the decreasing and increasing portions of the temperature cycle. Figure 3-11 shows the same data but with a thermal rate compensation factor added to the static polynomial temperature compensation. It will be noted that the previous differential offset has been markedly reduced.

Figure 3-12 and Figure 3-13 show similar results for another run, several days later, at a higher thermal rate (slightly in excess of  $\pm 1^{\circ}$ C/minute). Figure 3-12 shows test results with only static temperature compensation employed. Figure 3-13, with a noticeably smaller deviation differential, is based on the same rate compensation factor used in Figure 3-11 (namely,  $K = -1 \times 10^{-2}$  $10^{-6}$  per °C/second, and K(2) = -0.005). Inspection of Figure 3-13 indicates a small measure of overcompensation in the thermal rate factor. A value in the proximity of  $K = -0.9 \times 10^{-6}$  would perhaps have provided better rate compensation over the full temperature cycle of this particular run. Figures 3-14 and 3-15, for the case of an intermediate thermal cycle over the low temperature region of -8°C to -32°C and return, again illustrate the advantages of incorporating thermal rate compensation. We again see evidence of overcompensation if we employ the "baseline" values of  $K = -1 \times 10^{-6}$  and K(2) = -0.005 that had been derived from the data in Figure 3-11.

From these data it can be concluded that the linear form of thermal rate compensation employed in these tests, although

\*\*\* STANDARD DEVIATION (^F/F) = 2.0973929913E-8

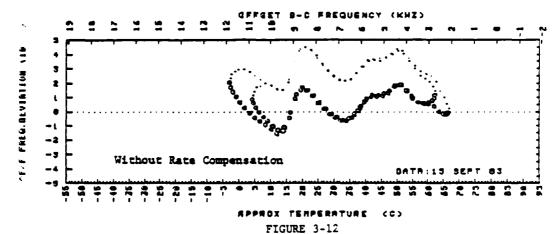
\*\*\* AVE ABSOLUTE DEVIATION (^F/F) = 1.71207253927E-8

\*\*\* AVE FRED DEVIATION(^F/F) = 1.47775416312E-8

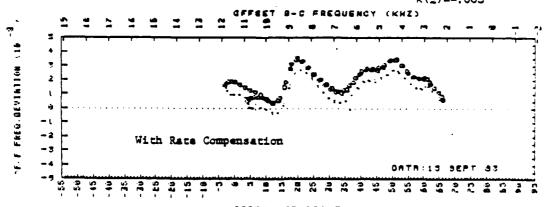
\*\*ACCUMULATED TIME RATE ERROR(MILLISECONDS/DAY) = 1.27677959694

THERMAL SHOCK COEFFICIENT(^F/F PER DEG C/SECOND): 0

K(2) = 0



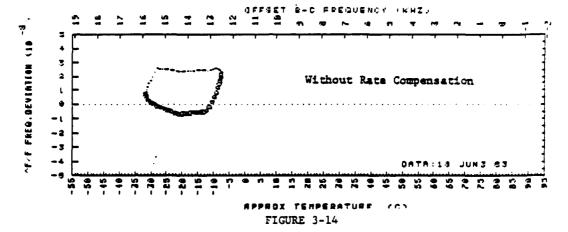
THERMAL SHOCK COEFFICIENT(^F/F PER DES C/SECOND): -.000001

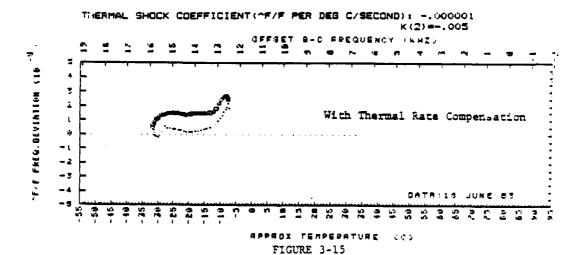


APPROX TEMPERATURE (C) FIGURE 3-13

THERMAL SHOCK COEFFICIENT (^F/F PER DEG C/SECOND): 0

K(2) = 0

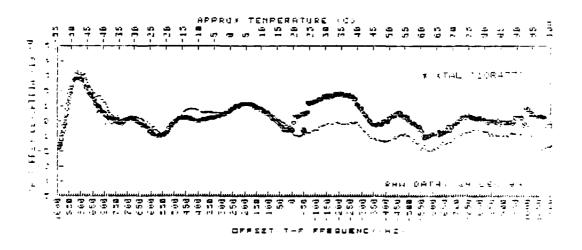




offering a very useful and significant improvement in accuracy, does not provide complete compensation over varying environmental conditions. A non-linear expression (e.g., one using the square root of the measured thermal rate) or, alternatively, inclusion of a thermal acceleration term might, on an empirical basis, give better results over a wider range of environmental conditions.

A portion of the observed frequency displacement during temperature cycling may be due to hysteresis; however, it is difficult to separate hysteresis effects from the residual frequency differencies that are observed at the lowest thermal rates  $(\pm 5^{\circ}\text{C})$  per hour) used in some of the environmental testing.

Figure 3-16 illustrates the comparative frequency deviation pattern of an SC-cut 10MHz crystal cut to have a lower turnover temperature in the vicinity of +5°C for the C-mode (3rd overtone) frequency. The dotted trace shows the response for decreasing temperatures; the heavier trace shows the increasing temperature portions of the thermal ramp cycle (at the slow rate of ±0.25°C/minute). This pattern differs from the previous plots in that the thermal transient behavior appears to reverse polarity in the neighborhood of the turning point: at elevated temperatures, the observed deviation for decreasing temperatures falls below the readings for increasing temperatures. Also, it appears that the thermal shock (or hysteresis) effect is relatively small throughout the low temperature region.



Thermal rate: 0.25°C/Minute

FIGURE 3-16

It should be recognized that plotting of the data in terms of the frequency deviation from any particular polynomial or other analytic "baseline reference" is an expedient that facilitates data analysis and interpretation. The observed deviation and structure of the "frequency deviation" pattern depends to a considerable extent upon the assumed degree of the polynomial. If too low a degree is selected (e.g., linear, quadratic, or even cubic), the resultant deviation values will be excessively large (thereby requiring a less sensitive and less useful scale factor for the data plotting). On the other hand, use of a high degree polynomial (e.g., 9th or 10th), although capable of reducing the apparent deviation values, probably detracts, rather than assists, in the data interpretation process.

The accuracy attainable by an operational ECXO system is not necessarily limited by the apparent deviation relative to any polynomial approximation. With a suitably designed "look-up" compensation table, for example, the individual table values can more closely match the actual frequency behavior of the resonator or ECXO oscillator. The ultimate accuracy will then be determined by any lack of repeatability in oscillator performance, together with the quality of the "look-up" table and associated interpolation procedure.

### SECTION 4

### SUMMARY AND CONCLUSIONS

### 4.1 SUMMARY AND CONCLUSIONS

The program has achieved a major objective in that it has produced a better understanding of the behavior and inter-relationship of the B-mode and C-mode frequencies of SC-cut quartz resonators. The investigation has demonstrated that high stability, re-traceability, and accuracy are intrinsic to dual mode operation of such resonators. The experimental results show that the stability and retraceability of the dual B-mode and C-mode frequencies, except in narrow temperature regions where a B-mode activity dip is encountered, is capable of providing a frequency accuracy of several parts in 10<sup>8</sup> over an extended temperature range of -55°C to +100°C. This potential represents a 10 - 100 fold improvement over conventional TCXO oscillators using analog-voltage varactors for frequency compensation.

The B-mode activity dip in some crystals results in a moderately small frequency perturbation over a limited temperature span (e.g., a discontinuity of 3 x 10<sup>-8</sup> over a few degrees Celsius). In other crystals, however, the interference may be so severe that normal oscillation ceases. The question must therefore be raised whether the B-mode activity dip problem can be eliminated (or circumvented) by modification of the crystal design. Is it feasible, for example, to design an SC-cut crystal so that any activity dip, if present at all, will fall outside the normal operational temperature range? (Several of

the resonators used in this study had a single activity dip in the neighborhood of +65°C. Could this interference temperature region be increased to +85°C, or even higher, without introducing another dip at some lower temperature?) Or, is it feasible to dimension or contour the crystal to suppress interfering modal signals to a sufficiently low level so that the interference effect will not be too great? In summary, the activity dip problem appears to be the most severe obstacle to the use of dual B-mode and C-mode frequencies for ECXO compensation purposes.

On the positive side, the B-C differential frequency mode of operation appears to offer several significant advantages over alternative techniques of measuring resonator temperature. Use of the B-mode frequency provides a high frequency vs. temperature sensitivity. There is roughly a 20 kHz change in the B-C frequency over the -55°C to +95°C range with a 5 MHz SC-cut resonator (corresponding to a slope in excess of 26 ppm/°C normalized to the C-mode frequency). This high sensitivity relaxes the resolution and precision requirements of the digital counter required within an operational ECXO.

The excellent performance observed at the low temperature extreme was not anticipated prior to the investigation. It had been thought that the stability and accuracy of the dual-mode compensation technique would deteriorate because of the steep slope of the C-mode frequency vs. temperature characteristic in this region (greater than 2 ppm $^{\rm C}$ /C). To achieve a frequency compensation precision of  $\pm 1 \times 10^{-8}$  with this severe C-mode slope

implies a thermometry error of less than  $\pm 0.005^{\circ}$ C for the C-mode frequency.

With TCXO oscillators, the crystal's cut angle and turnover temperature must be carefully chosen so as to minimize either the maximum slope or the maximum frequency excursion over some selected temperature region. From the results of this investigation it does not appear necessary to put the same restriction on SC-cut quartz resonators to be used in dual mode ECXO applications. A steeper frequency vs. temperature slope may require a wider range or higher resolution in the ECXO look-up table or compensation algorithm, but that is a distinct problem from the question of the intrinsic stability of the quartz resonator. Specification of the lower turnover temperature of an SC-cut crystal intended for dual mode (B- and C-mode) ECXO operation will be determined, not by an intrinsic instability of the quartz material at either temperature extreme, but rather, by the minimum spacing of the stored compensation values in the look-up table together with the quality of the interpolation algorithm used for intermediate temperature points.

It needs to be recognized that the factors that limit the ultimate performance of an ECXO oscillator, including the limitations of the resonator itself, have not yet been fully established. Design criteria that have been developed over the past decades for conventional TCXO oscillators are not likely to be applicable to the development of ECXO systems.

The contract study has also demonstrated that thermal

transient effects cannot be neglected if high clock accuracy is to be achieved. Temperature rates as low as  $\pm 5^{\circ}$ C/hour during temperature cycling produced noticeable frequency offsets. Some of this deviation may be due to "hysteresis"; however, a better method of defining and measurement of "hysteresis" under changing conditions of temperature cycling (with variable temperature limits and under different rates of change) appears desireable.

The test results to date show a significant improvement if some degree of thermal rate compensation is used to augment the fundamental compensation for frequency-temperature dependency. Further investigation will be required to determine the most appropriate rate compensation algorithm that will provide "best" performance, in an empirical sense, over a wide range of realistic environmental conditions.

All of the test data presented in this report are shown as frequency deviations from either a 5th or 6th degree power polynomial. This procedure allows the individual raw data points to be graphically displayed to a high resolution level on a single plot covering the entire temperature range. An operational ECXO unit, however, is likely to employ a detailed look-up table in which the stored compensation values follow the actual, measured data points rather than the assumed polynomial approximation. The scatter and retraceability of the data, rather than the deviation from an arbitrary approximation, then provides a good measure of frequency accuracy.

Inspection of all data for the various runs indicates that

an average frequency accuracy of several parts in 10<sup>8</sup> (for the SC-cut quartz resonator elements) is attainable with dual mode frequency compensation. From this it can be concluded that an ECXO clock error of several millisecond/day, or less, is possible if the resonator performance is not seriously degraded by the oscillator circuitry or external compensation processing. There remains, finally, the problem of aging and frequency recalibration. All operational ECXO clock devices must include a suitable mechanism for both periodic time synchronization and periodic frequency calibration (syntonization). Any realistic estimate of clock error must take into account the probable (cr worst case) error in syntonization and the time interval between time updating under anticipated military usage conditions.

### APPENDIX A

### MEMCRANDUM

FROM: Bob Nelson

TO: Donnell, Baltzer, Stone, Quinones

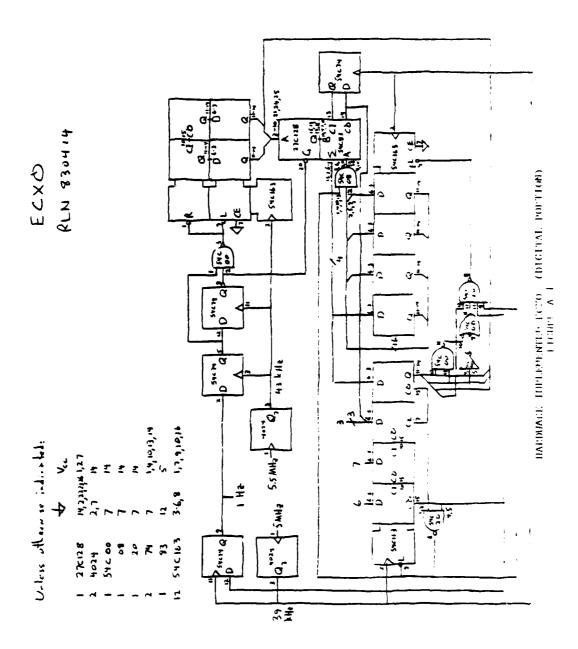
SUBJECT: A Hardware-type ECXO Digital Compensation Circuit

Figure A-1 shows a design for a hardware-type ECXO compensation circuit.

The B-mode (5.5 MHz) and C-mode (5 MHz) crystal outputs are first prescaled to 43 and 39 kHz respectively. The 39 kHz is divided by the lower-left programmable divider to 1 Hz. This divider is preset with a value between 26464 and 26480, for a division ratio between 39072 and 39056, or 5001216 and 4999168 overall, respectively. This range of division ratios corresponds to the range of C-mode frequency which the design can tolerate.

The exact division ratio is determined by the value, 0 to 16, to which the 5 lowest divider bits are preset. This value is the 5 upper bits of the 21-bit sum of a 20-bit stored correction with a 16-bit remainder from the previous such summation. The use of the saved remainder to bias subsequent corrections means that the 16 lower bits of the correction have the same effect on the average as if they actually preset the divider with a 4-bit integer and a 16-bit fraction.

The relationship between the stored correction, K, and the C-mode frequency, f, may be seen by realizing that the fixed preset, plus the correction, plus the counts caused by the 39 kHz



clock must total to the full range of the divider,  $2^{16}$  Hz or  $3.90625 \times 10^{-10} \times f$  (at f = 5 MHz).

The summation is done in serial by 4-bit words. The impending overflow of the divider is detected and used to enable shifting by fours of the 16-bit remainder register (lower-right). As each hexadecimal digit is shifted off the right end of the register, a correction digit from the 27C128 memory is added to it and the sum stored in the left end of the register. A single 54C74 flip-flop saves the carry. After 4 shifts, the register is back to normal and has been incremented by the 16 lower correction bits. The last 4 upper correction bits are added to the carry in the last period before divider overflow and stored in the 5 lower divider bits along with the constant 26464 (6760<sub>16</sub>) in the 11 upper bits when the divider is preset at overflow.

Only part of the 16384 x 8 correction memory is actually used. The corrections are stored as 5 x 256 x 4, but another 256 x 4 area must contain zero to insure that the carry flip-flop is cleared before the first summation. The memory map is

00000XXXXXXXX	XXXXXXXX	
000010XXXXXXX	0000XXXX	
000011AAAAAAA	XXXXKKKK	(LSW)
000100AAAAAAA	XXXXXXXX	
000101AAAAAAA	XXXXXXXX	
000110AAAAAAA	XXXXXXXX	
000111AAAAAAA	XXXXXXXX	(MSW)
All Other Locations	XXXXXXX	

DATA

**ADDRESS** 

A = correction address K = correction

If desired, the 3 upper address bits could be used to select among 8 sets of corrections to allow a small ageing adjustment, or to produce intentional frequency offsets.

The corrections are selected from second to second by counting the 43 kHz prescaled B-mode signal in the 8-bit counter in the upper-right. This counter, of course, overflows many times during the second, but its final values cover a range of about

(5.5 MHz x  $2^{-7}$  x 1 sec) x (26 x  $10^{-6}$ /C x 140C) = 156. This assumes a 26 ppm/C frequency vs temperature slope for B-mode and a 140° temperature span.

As the divider approaches overflow, the output flip-flop in the upper-left is set synchronous with the 39-kHz clock. Its output is then synchronized with the 43-kHz clock and the rising edge detected. This sychronously resets the counter and loads its final count into the 8-bit address register. Simultaneously, the memory is enabled through the end of the summation process. The count copied into the address register is always one less than the correct value (module 2<sup>15</sup>), because one count is lost to resetting the counter.

### APPENDIX B

```
. :==
        in Diam " *
                                                                       . ..
                           PROGRAM 'REGR/2107'
120 DISP
                                                                       . . .
.mb 0168 " *
NO WIEF " X
                        Nth DEGREE POLYNOMIAL FIT
                                                                840111 *"
150 DISP " *
170 PRINTER IS 705
130 MASS STORAGE IS ":D711" ' Change to ':D700' if naw data on floppy disk
20% BRINT "* THIS PROGRAM , 'REGR/2107, RETRIEVES RAW DATA FILE, SELECTS *"
Ito BRINT "* CERTAIN DATA PAIRS (BY USING STEPS, FORMS AN NEW DEGREE POLY-*"
20 PRINT "* NOMIAL FROM THESE SELECTED FOINTS. AND USES THIS POLYMOMIAL *"
            TO ANALYZE ENTIRE DATA SET. DATA PRINTOUT IS GIVEN IN TERMS *"
221 PRINT "*
200 SPINT "* OF FREQUENCY DEVIATION FROM THIS COMPENSATION POLYNOMIAL:
ITO PRINT "* ALSO, A GRAPHICAL PLOT OF THESE POINTS CAN BE 'DUMPED'.
252 SPINT "* *OPERATOR MUST INPUT SYNTHESIZER FREQ 'NOMF(x)' AS STORED IN *"
154 PRINT "* RAW DATA FILE 'HEADER1' (SEE PROGRAM 'DATA/PLOTI'). ALSO.
155 PRINT "* OPERATOR MUST INPUT INFO ON CRYSTAL SELECTED DATA PAIRS.ETC
ITO PRINT
                               .DATA FILE NAME: ?" @ INPUT DSK$.DATFIL*
DOC DISP "INPUT DISK#:
310 PRINT "DATA STORED ON DISK: ":DSK#:TAB (40):DATFIL#:TAB (60):DATE :TIME
320 01M A(13).R(7.8).T(8).B(2100,6).COMMENT1$02001.COMMENT2$02001.COMMENT3$02003
TTO REM KX Above DIM A.R.&T permits up to 6th degree polynomial:DIM B permits
2100 lines of raw data * 6 variables (ind TIME)
14% DISP " INPUT: CRYSTAL TYPE: SERIAL NO.FREQUENCIES.ETC(18 CHAR MAX/COMMA) ""
ISO INPUT TYPES.SERIALS.FREQS.QVRTQNES.OTES.YEARS.ETCS
THE PRINT "CRYSTAL TYPE: ":
 TO PRINT TYPES.SERIALS, FREQS, OVRTONES, DTES, YEARS, ETCS
720 FOR J#1 TO 4
 TO DISH "INPUT SYNTHESIZER FREQUENCY. NOMF(":J:"):" @ INPUT NOMF(J:
                SYNTHESIZER FREQUENCY, NOMF(":J:"):":NOMF(J)
ON PRINT "
410 MEXT J
120 DISP "ANY ADDITIONAL COMMENTS (UP TO 200 CHARACTERS--NO COMMAS!) ?"
400 INPUT COMMENTIS
440 PRINT "NOTE: ":COMMENTIS
451 PRINT
42 - DISP "DEGREE OF EQUATIONS"
470 PRINT "DEGREE OF EQUATION":
48" INPUT D
490 PRINT D
the cise "Total number of RAW DATA POINTS IN RUND"! Must be known or estimated
510 PRINT "TOTAL NUMBER OF DATA PAIRS=":
SEC IMPUT FOFAL
STO PRINT TOTAL
Supposes "Beginning Data Pair NO.7(for deriving polynomial deethidlents)"
EEO IMPUT L
SER PRINT "BEGINNING DATA FAIR.L=":L
 TWO DIEP MENDING DATA PAIR NO. Tefor deriving polynomial coefficients?
THE CHEUT H
190 PRINT "ENDING DATA PAIR. M=":M
SHY DISP "STEP BITET(for deriving polynomial coefficients)"
JID IMPUT 5
42 - PFINT "STEP SIZE.S=":S
SOCIETHINT (CM-L) (S)
SAC SEINT "NUMBER OF POINTS USED TO DETERMINE ROLYHOMIAL FITCHS": 12
 IS DISE MUMBER OF FOIRTS USED TO DETERMINE POLYNOMIAL TITETON
```

```
sel FRINT
 * 'a : " Y (HE) ": TAB (ST): "TIME": TAB (56): "TEMP(APPROX) "
5년이 라(1) =N 관 T(D+2) =0
590 FOR J=2 TO 2*0+1
700 ANDE0
210 MEXT J
20 FOR N=1 TO D+1
773 Tibb=0
T40 NEXT K
TEO ASSIGN# 1 TO "XTALDATx" ! NOTE:Must match disk file name! **********
'ay FOR [=1 TO FOTAL
TO FOR J=1 TO 5
780 READ# 1 : 8(I.J)
TRO NEXT J
900 B(I.i)=NOMF(I)/10.24*(B(I.1)+10^7) @ B(I.3)=NOMF(I)/10.24*(B(I.3)+10^7)
Sig B(I.2)=NOMF(2)/10.24*(B(I.2)+10^7) ! Translates to F-mode frequency
322 8(I.5)=NOMF(4)/10.24*(B(I.5)+10^7) ! Translates back to S-mode freq
3TO 3(I.4)=NOMF(3)/10.24*(B(I.4)+10^7) ! Translates back to B-mode freq
340 NEXT I
850 FOR I=L TO M STEP S
366\% (=(S(I,1)+B(I,3))/2-B(I,2)-XCONST ! Operator must replace XCONST with a
numeric chosen to reduce magnitude of X over the temperature raange
370 Y=8(I.2)-YCONST ! Operatore must replace YCONST with a bias so as to reduce
" to near O
C30 TAPPROX=-((8(I.4)-8(I.5)-470000)/138)+85 ! Uses old 8-0 mode temp approx
90 FFINT USING 900 : I.(B(I.1)+B(I.3))/2.B(I.2),X.Y.B(I.6).TAPPROX
우아의 [MAGE 40.2X.8D.4D.1X.8D.4D.1X.84Z.3D.1X.83Z.4D.3X,5D.6X.83D.2D
P20 REM * FOLLOWING PORTION USED TO DERIVE THE POLYNOMIAL APPROXIMATION.P *
940 FOR J=2 FO 2*D+1
950 A:U:=A(J)+X^(J-1)
yao NEXT J
- TO FOR F=1 TO D+1
-80 R(F.D+2)=T(K)+Y*X^(K-1)
990 T(k) #T(k) +Y*X^(K-1)
1000 NEXT K
1010 F(0+2) =T(0+2) +Y02
1920 NEKT I
1950 FOR J=1 TO D+1
1 H40 FOR K=1 TO D+1
1050 R(J.K)=A(J+K-1)
1960 NEXT K
1070 NEST J
1080 FOR J=1 TO D+1
()90 % ≖J
1100 IF R(K,J) to 0 THEN 1150
1110 8:48 +1
1120 IF FOR D+1 THEN 1100
1100 PRINT " NO UNIQUE SOLUTION"
1140 GOTO 1750
1150 FUR I=1 TO D+2
1150 S#R(J.I)
1170 お(は.1) 神代(株.1)
1180 R(K.[)=S
1190 NEXT I
1200 Z=1/R(J.J)
1010 FOR I=1 TO 0+2
:120 S.J.I:=1#8(J.I)
```

```
1276 MEXT I
1240 FOR N#1 TO 0+1
:250 IF <=J THEN 1300
1130 I=-R(K.J)
1270 FOR I=1 TO D+2
1220 S(K.I)=R(K.I)+Z*R(J.I)
1290 NEXT I
1700 NEXT K
1310 NEXT J
JJ20 PRINT
 ITO PRINT "
                          CONSTANT (AQ)
                                            =":R(1,D+2)
:T40 FOR J=1 TO D
1350 PRINT J: "DEGREE COEFFICIENT (A":J:") =":R(J+1.0+2)
1360 NEXT J
:370 PRINT "
                   ~Y(IDEAL)=A0+(A1*X)+(A2*(X*X))+....(An*(X*n)) "
1080 PRINT
1390 Pe0
1400 FOR J=2 TO D+1
1410 F=P+R(J,D+2)*(T(J)-A(J)*T(1)/N)
1420 NEXT J
1400 Q=F(D+2)-T(1)-2/N
1440 Z=Q-P
1450 I=N-D-1
1450 PRINT
1470 J=P/0
:480 PRINT "COEFFICIENT OF DETERMINATION (R^2) =":J
1490 PRINT "COEFFICIENT OF CORRELATION
1500 PRINT "STANDARD ERROR OF ESTIMATE(HZ)
                                               =":SQR (J)
                                                =":SQR (Z/I)
1510 PRINT "STANDARD DEVIATION (^F/F)
                                                =":SQR (Z/N)/NOMF(2)/1006
1520 REM ******END OF POLYNOMIAL ROUTINE **************************
1530 PRINT @ PRINT
1540 SEEP JO. 2000
1550 ALPHA
1550 DISP "INPUT NEW BEGINNING, ENDING DATA PAIRS, AND STEP SIZE(OR TRESET) TO E
ND RUND"
1570 INPUT L.M.S
1590 PRINT " BEGINNING. ENDING DATA PAIRS, AND STEP SIZE: ":L:M:S
1500 PRINT @ PRINT
1200 BEER 10,100
'510 DISP "INPUT DATE OF RAW DATA RUN (IN FORMAT 'DAY MONTH YEAR')"
1520 INPUT RDATES
1500 DISP "ANY ADDITIONAL COMMENTS (UP TO 200 CHARACTERS--NO COMMAS!)"
1840 INPUT COMMENTES
1550 PRINT " NOTE: ":COMMENT2# @ PRINT
1550 PRINT TAB (2): "NO. ": TAB (7): "THEREQ(HZ) ": TAB (20): "FHEREQ(HZ) ": TAB (34): "Y
HITT:FAB (43):"CC(IDEAL)":TAB (53):" DEV(cF/F)":TAB (66):"TEMP":TAB (73):"TIME"
1870 PRINT "----
1520 5=0 @ H=0 @ PRNT=0
1590 FOR I=L TO M STEP S
1700 N=1+[NT ((M-L)/S) @ PRNT=PRNT+1
1710 K=(B(I.1)+B(I.5))/2-B(I.2)-KCONST ! Difference freq.with offset.in Ho.
   20 Y=8(I.2)-YCONST ! YCONST to be replaced with numeric
: TO TAPPROX=-((B(I.4)-B(I.5)-470000)/138)+83 ^{\circ} Temperature approx based on 3-2
 difterance frequency
  (40 P#R(1.D+2)
 :750 FOR J≠L TO D
17:00 P#F+R(J+1.D+2)*K^J ! Simple temperature approximithout thermal rate come
THERE J
1730 HEH47Y-PN C W G#G+ABS (Y-P)
```

```
75 0138 USING 1920 : I.(9(1.1)+8(1.3))/2.8(I.3),(.8.(Y-8) NDMF/2010 E.TARHADA
. 3 I. =
:800 (F PRNT=10 THEN 1810 ELGE 1940 / Prints every 10th line in sample(sted 3)
:3:. PRINT USING 1820 : I.(8(I.1)+8(I.3))/2.8(I.2).X.P.(Y-P)/NOMF(2)/10 5.TARFEC
A.B+1.53
320 [MAGE 40.1x.80.30.1x.80.30.1x.840.30.1x.840.30.1x.840.30.1x.31z.20e.2x.330.20.2x.30
.930 SBNT=0
1 TRBM HELL
1850 U=(4/N) 1.5/NOMF(2)/1006 @ F=G/N/NOMF(2)/1006 @ PRINT
1850 PRINT TAB (5): "*** STANDARD DEVIATION (^F/F)
                                                  = ":⊔
 270 FRINT TAB (5): "*** AVE ABSOLUTE DEVIATION ("F/F) = ":F 9 FRINT
1820 BOSUB 2190
:39: GOSUB 1970
1900 SEEP 00.2500 @ GOTO 1550
1910 PRINT "
1923 END
1930 k0LD=0
1940 FOR I=L TO M STEP S
1950 \forall = (B(I,1) + B(I,3))/2 - B(I,2) - 172000
1980 Y=B(I.2)-10001000
1970 TAPPROX=-((B(I.4)-B(I.5)-470000)/138)+83 ! Temperature approx based on B-C
of second SC-cut xtal
1980 P=R(1,D+2)
1990 FOR J=1 TO D
2000 P=P+R(J+1,D+2)*X^J
2010 MEXT J
2020 V=(Y-F) *100/NOMF(2) ! Sets vertical scale to 5*10^-8
2030 REM **** Delated ' PRINT I:X.V.P ' on 2 Dec 83
2040 MOVE K.V
2050 IF XOLDKX THEN 2060 ELSE 2070
20%0 LABEL "." @ BEEP 10.100 @ GDTO 2080 ! Labels decreasing temp points
2070 LABEL "o" @ BEEP 15.100 ! Labels increasing temp points
2080 (GLD=X
2090 NEXT I
2100 BESP 40,1000 @ BEEP 30,1000
2110 WAIT 20000
2120 DUMP GRAPHICS
0100 ALPHA
2140 DISP "ADD COMMENTS (REPEAT TYPE OF CRYSTAL, DATE RAW DATA.ETC(NO COMMAE)"
1150 INPUT COMMENTS®
0160 PRINT @ PRINT COMMENTS:
1170 RETURN
2190 PEM ***
                    FOLLOWING PLOTS THE FRAME AND AXES
                                                                     ***
2210 CLEAR
L220 PLITTER IS 1
22TO C=5 * #######C=5 gives full scale vertical Y-AXIS=+/-5#10 +6
 1140 GRAPHALL
225% LCCATE 20.200.15.80
 1250 FRAME
3270 DEG
2280 REM ** KMAX and KMIN must be modified to match observed KMAX and KMID.
1190 FEM ** Also, all other horizontal scale values may need to be modified to
erie correct label positioning
2700 xMAX=1000 \theta XMIN=-1200 ^{+} Adjust to observed XMAX and XMIN for test stat 2710 CS12E ^{+}
2020 SCALE KMAY.XMIN.-C.C
2000 YAKIS KMIN..S.-C.C
```

```
27 M CAKES 10.1.KMAX.-0.5.3.4
2750 MOVE (MAX-750.-01.45%C)
2360 C3125 4
2370 C085L "OFFSET THE FREQUENCY (HZ)"
1780 MOVE XMAX-1400.-(.9*C)
CORP CBICE 4
Class Label "RAW DATA: ":RDATE*
2410 MOVE KMAX-600.1.4*C
141: CSIZE 4
2430 LABEL "APPROX TEMPERATURE (C)"
2440 MOVE XMAX+100.-(.95*C)
1450 CEG
2469 LDIR 90
1470 LABEL 10F/F FREQ.DEVIATION (10
2480 MOVE XMAX+115..95*C
2490 LABEL "-8"
2500 MOVE XMAX+1.0
2510 LINE TYPE 3
2520 DRAW XMIN.O
2530 T=-55
2540 FOR I=0 TO 31 STEP 1 ! * Gives temperature span from -55 to +95 C
2550 X=KMAX-10-IK(XMAX-XMIN)/31
2560 MOVE X.1.05*C
2570 LABEL T+5*I
2580 MOVE X..95*C
1590 LABEL "-"
1500 NEXT I
1510 RETURN
```

### APPENDIX C

110 FRINT "\* PROGRAM DATA/FLOT: REVISED 1-10-34 170 PRINT 140 PRINTER IS 705 150 PRINT "\* THIS PROGRAM "DATA/PLOTX" CONTROLS 4 CHANNELS OF MODEL 2107 170 PRINT "\* REFLECT<mark>OMETER.STORES & RAW COUNTER READINGS ON DIS</mark>K. PRINTS OUT 130 FRINT "\* B&C MODE FREQ(5.48%5.00MHZ IN THIS RUN) FOR THE TEST RESONATOR 190 PRINT "\* (CHANNELS O & 1) AND THE B & C-MODE FREQUENCIES OF A REFERENCE 20% PHINT "\* CRYSTAL (COLORADO CRYSTAL CO :S/N 1) USED TO MEASURE APPROXIMATE \*\* 310 PRINT "\* OVEN TEMPERATURE. THE T-MODE FREQUENCY OF THE TEST CRYSTAL IS . PRINT "\* ASSIGNED TO CHANNEL O: F-MODE FREQ TO CHANNEL 1. THE B-MODE x ·· 230 PRINT "\* OF THE REFERENCE CRYSTAL IS ASSIGNED TO CHANNEL 2: C-MODE TO \* " 249 PRINT "\* CHANNEL 3. IF THE PROPER POLYNOMIAL COEFFICIENTS ARE KNOWN FOR 250 SRINT "\* THE TEST CRYSTAL AND KEYED IN BY THE OPERATOR. THE SREQUENCY \* " 350 PRINT "\* DEVIATION OF F-MODE FREQ RELATIVE TO THE PREDICTED POLYNOMIAL \* ·· LTO FRINT "\* VALUE WILL BE PRINTED OUT AND ALSO PLOTTED(ON THE HP-87 CRT) 190 PRINT 310 FRINT "\* NOTE: VARIOUS CONSTANTS IN THIS PROGRAM MUST BE MODIFIED TO FIT \*" TO PRINT "\* THE SPECIFIC CRYSTALS TO BE USED. CONSTANTS USED HERE APPLY TO \*" TTO PRINT "\* COLORADO CRYSTAL SZN 2 IN CHAN 0/1 % COLORADO CRYSTAL BZN 1 IN-140 PRINT "\* CHAN 2/3. ALSO, THE OPERATOR SHOULD CAREFULLY FOLLOW 'INFUT' TEG FRINT "\* INSTRUCTION ON CRYSTAL I.D..SYNTHESIZER FREQUENCIES(MODEL 2107).\*" Tab RRINT "\* PLANNED TEMPERATURE PROFILE.ETC. THIS INFO TO BE STORED ON FILE \*" TTO PRINT "\* NAMED 'HEADERX':ALL COUNTER FREQ READINGS STORED ON 'XTAL/DATA: \*" EO PRINT "\* FILE. 1-10-94 **X** 11 +00 PRINT 410 PRINT >>20 01M [PROFILE\$[160], IDENT\$(4)[128].MODE\$(4)[64].COMMENT1\$[160].R(10.10) 400 MASS STORAGE IS ":D700" ! Uses floppy: Winchester requires different address 450 CREATE "HEADER1:D700".1.1028 ! \*Change to 'HEADERY' or purge file if HEADER1 already used as data file name 450 ASSIGN# 1 TO "HEADER1" ! \*Must match name in above line 479 CREATE "XTALDATA: D700".7.8000 ! Check CAT to ensure no duplication 430 ASSIGN# 2 TO "XTALDATA: D700" ! Open a floppy disc file AND FILE NAMET: " 9 INPUT FLORS 490 DISP "RAW DATA TO BE STORED ON DISK#xxx?: 9 INPUT PHILES 500 PRINT @ PRINT " DISK#": FLOP4: "FILE: ": PHILE4: TAB (65): DATE : TIME 510 DISP "INPUT PRESENT DATE (IN FORM '21 DEC 84')" @ INPUT DIE\$ \$20 DISP "INPUT APPROX TIME THAT RUN WILL START(INCLUDING TAME OR TEMT) F @ INFUT ME 500 DISP "PLANNED MAX TEMP (Number only--degreesC)" @ INPUT TMAX

S40 DISP "PLANNED MIN TEMP (Number only-degreesC)" @ INFUT TMIN S50 ARINT "TMAX= ":TMAX:" oC":TAB (20):"TMIN= ":TMIN:" oC"

550 OISP "PLANNED TEMERATURE PROFILE-(2 typed lines max ')" @ INPUT TEROFILES S70 PRINT "FLOPPY DISK#":FLOPS:TAB (45):"RUN STARTED:":DTEs:" ":TYMES S80 PRINT "PLANNED TEMPERATURE PROFILE: ":TPROFILES S70 OISP "ADDITIONAL COMMENTS? (Up to 2 typed lines: if none.kevin 'M':no commas of @ INPUT COMMENTIS @ DISP @ DISP # DISP # OFFINT "NOTE:":COMMENTIS @ DISP @ DISP # DI

```
:In 755 (=0 f0 I / Assumes only 4 reflectometer channels in use. With Channel
     Pannel I used twice in each cycle to provide 5 haw data channels
s4 - DISE "CHANNEL#":[:" :[NPUT CRYSTAL MER& IDENT (But no Commas')" @ iNPUT [DEN
* * *
SEV SISE "CHANNELD":1:" :INPUT OPERATING MODE & QVERTONE/FUND (18 char max)":9 1
 FLI MODES: 12
 .av 013F "CHANNEL#":1:" :INPUT ASSOCIATED SYNTHESIZER FREQ (In MHz units--no alb
ha chanacters:)":@ INPUT NOMF(I)
STY SRINT TAB (2):I:TAB (7):IDENT#(I):TAB (45):MODE#(I):TAB (T0):NOMF(I)
GBC FRINT# 1 : IDENT$(I).MODE$(I).NOMF(I)
SER MEXT I
 TOO FOR ISO TO D
TIO CISP "****** BE SURE TO KEY IN SOME 'NUMERIC' FOR THE FOLLOWING *******
 10 DISP "INCIDENT CRYSTAL POWER(MICROWATTS): CHAN#":1 👳 INPUT FWR(I)
TIO PRINT TAB (10): "INCIDENT CRYSTAL POWER: CHANNEL#": I: ": ": PWR(I): "MICROWATT"
740 PRINT# 1 : PWR(I)
750 NEXT I
TSC PRINT
770 FRINT "***** ASSUMED POLYNOMIAL COEFFICIENTS *************************
****
790 9=6 ! Allows for a 6th order polynomial
'90 DISP "IF POLY COEFFICIENTS ARE NOT KNOWN, KEY IN '0' FOR EACH OF THE FOLLOWIN
800 DISP " INPUT THE DESIRED POLYNOMIAL COEFFICIENTS . THE PROGRAM "
310 DISF " ALLOWS SIXTH-ORDER COEFFICIENTS TO BE KEYED IN.
320 DISP " FOR A FIFTH ORDER POLYNOMIAL . KEY IN A(4) =0. " @ DISP @ DISP
850 DISP
840 DISP "CONSTANT A(0):":@ INPUT R(1.D+2)@ PRINT "
                                                       A(0) = ":R(1.D+2)
850 DISP "COEFF.
                    A(1):":@ INPUT R(2,0+2)@ PRINT "
                                                       A(1) = ":R(2.D+2)
350 DISP "COEFF.
                    A(2):":@ INPUT R(3.D+2)@ PRINT "
                                                       A(2) = "(R(3,D+2))
970 DISP "COEFF.
                    A(3):":@ INPUT R(4,D+2)@ PRINT "
                                                       A(3) = "R(4, 0+2)
39" DISP "COEFF.
                    A(4):":@ INPUT R(5,0+2)@ PRINT "
                                                       A(4) =":R(5.D+2)
See DISP "COEFF.
                    A(5):":@ INPUT R(5,D+2)@ PRINT "
                                                       A(5) =":R(5,D+2)
eco DISP "COEFF.
                    A(6): ": @ INPUT R(7.D+2) @ PRINT "
                                                       A(4) = ":R(7.0+2)
PIG OF FEY# 7 GOTO 840 @ WAIT 10000 ! USED TO 'ESCAPE' ANY TYPING ERROR
910 FOR I=1 TO 7
900 PRINT# 1 : R(I.D+2)
HALL NEXT I
750 FRINT "$$$$$ F= A(0)+ A(1)$X +A(2)$X^2 + ....+A(n)$X^n = $$$$$$$$$$$$$
PHO ASSIGN# 1 TO
H70 PRINT @ PRINT
990 PRINT "NO.":TAB (7):"T-MODE(HZ)":TAB (22):"AT":TAB (29):"F-MODE(HZ)":TAB (42
-:"F/DIF":TAB (49):"TAPPROX":TAB (60):"TIME":TAB (70):"^F/F"
990 DISP "THE FOLLOWING PORTION INPUTS VARIOUS FREQUENCIES FROM THE HESTISA"
1999 DISP "COUNTER AND STORES DATA ON THE FLOPPY DISC. A DATA FILE CALLED"
1510
     DISP " *KTALDATD* IS CREATED. check CAT for duplication!"
1020
     G05UB 1570
1070 LIME=0 9 SKIP=0 9 XOLD=0 9 COLD=0
1950 REM *** FOLLOWING SUBPROGRAM CONTROLS THE 2107 REFLECTOMETER/COUNTER ***
(0) 0 GN [[MER# 1.50000 GDTO 1090 | Gives 50 second cycle time: nav be modified
1080 SOTO 1080 | Idle loop for timer
1990 SUTFUT 706 : "93" @ SUTPUT 706 : "HH" | Multiplexer selects CHANNELS 313
1990 SUTPUT 707 : "FN1" | Switches to COUNTER A channel
1.19 MASE 500 / Reduced from earlier 5000 value**
1.10 ENTER 707 : CD ! Counter reading for Channel 2 to computer 1170 GUTPUT 707 : "FN17" ' Switches to COUNTER B channel
1140 ENTER 707 : CC / Counter reading for Channel I to computer
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1150 CUPSUI 707 : "SN1" : Switch back to COUNTER 4 channel
1110 WALT SOO
117 ENTER 707 : CA2 ! End reading of Channel 2 sent to computer
1130 OUTPUT 705 : "X3" : Multiplexer selects CHANNEL 0 %1
1190 GUIFUT 707 :"FN1" ! Switches to COUNTER A channel
:IDO SAIT 500 ! Reduced from earlier 5000 value
.210 ENTER '07 : CO ! Counter reading for Channel O to computer
  In dutrut 707 : "FN17" ! Switches to COUNTER B channel
1230 ENTER 707 : C1 : Counter reading for Channel 1 to computer
1240 OUTPUT 707 : "FN1" ! Second switch to COUNTER A channel
:250 ENTER 707 : CAO ! 2nd reading of Channel O sent to computer
1250 REM ** This second reading of Channel 0 is indicated by "CAO"
 TO REM ** Third reading would be CBx.etc.
1290 LINE=LINE+1
1290 PRINT# 2 : CO.C1.CAO.C2.C3.CA2.TIME
:300 F0=NDMF(0)/10.24*(C0+10^7) @ FA0=NDMF(0)/10.24*(CA0+10^7) ! Converts counts
r readings to xtal freqs
1310 Fi=NOMF(1)/10.24*(C1+10^7) @ F3=NOMF(3)/10.24*(C3+10^7) ! Converts to free
1320 F2=NOMF(2)/10.24*(C2+10^7) @ FA2=NOMF(2)/10.24*(C2+10^7) ! Convers to freq
1330 F10LD=F1 @ F20LD=F2 @ F30LD=F3 @ F00LD=F0
1340 FA00LD=FA(0) @ FA20LD=FA(2) ! Current F value becomes 'old' value
1350 TEMPCONST=83 ! Valid only for Colorado Crystal s/n 1
                                                         *****
1360 REM *** FOLLOWING CONVERSIONS NECESSARY TO MAKE USE OF A PREVIOUS PROGRAM
1070 BMODE1=F0 ! 1st B-MODE reading for crystal under test
1780 TMODE=F2 @ FMODE=F3 ! Used to give TAPPROX from B&C MODE operation @CHANQ/T
PRINT CHR#(27)&"11L"
1390 BMODE2=FA0 ! 2nd B-MODE reading crystal under test
1400 CMGDE=F1 ! In between C-MGDE reading for crystal under test
1410 TAPPROX=-((TMODE-FMODE-470000)/140)+TEMPCONST ! For use with Colorado s/ni
1420 X#(BMODE1+8MODE2)/2-CMODE-470000 ! B-C difference freq.with offset
1470 W=CMODE-5000000 ! Deviation in Hz | for C-Mode
1440 P=R(1.D+2) ! Inserts A(0) value
1450 FOR J=1 TO D
i4c0 P=P+R(J+1.D+2)*X^J ! Forms polynomial approximation value
1470 NEXT J
1480 CDEV=CMODE-COLD
1490 COLD=CMODE
1500 IF ABS (CDEV) 30 THEN BEEP 10.200
1510 IF ABS ($MODE1-BMODE2):300 THEN BEEP 99.200 ELSE 1520
1520 PRINT USING 1530 : LINE.BMODE1.BMODE1-BMODE2.CMODE.CDEV.TAFFROX.TIME .
2 10 5
1530 IMAGE 4D.1%.SD.3D.1%.S2D.3D.1%.SD.3D.1%.S2D.3D.1%.S3D.3D.5%.SD.4%.31D.3De
1550 REM * THE FOLLOWING SUBROUTINE WILL FLOT THE INDIVIDUAL FOINTS ON FLOT \star
15TO V=(W-P: #20 : ###Valid only for SKALE=5 & Freq=5 MHZ
1580 MOVE X.V
.590 IF :OLD</ THEN 1600 ELSE 1610
1500 LAPEL "." @ SEEP 10.100 @ GOTO 1620
151" LABEL "o" 9 SEEP 15.100
1520 KOLDEX
(53) REM - *** A long WAIT can be inserted here to slow down printput rate
1840 ON FEY# 1 GOTO 2080 ! Used to DUMP GRAPHICS
1550 GOTO 1650 ! Idle loop for cycle timer
1570 REM * THE FOLLOWING WILL PLOT THE FRAME AND THE AXES
1570 CLEAR 9 GCLEAR
TOO PLOTTER IS 1
1719 ShallEst
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1700 GRAPHALL
1770 ESCATE 20.200.20.87
1740 FRAME
LITE: DEG
1750 XMAX=19000 9 XMIN=+3000 ^{\circ} Valid for Colorado Crystal S/N 1:modify as red to CSIZE 4
1730 SCALE XMAX.XMIN.-SKALE.SKALE
1790 FAXIS XMIN..S.-SKALE.SKALE
1300 LAXES 200.1.XMAX.-SKALE.5..5.4
1910 MOVE xMAX-6000.-(1.45*SKALE)
1920 CSIZE 4
1870 LABEL "OFFSET THE FREQUENCY (HZ) "
1540 MOVE XMAX-14000.+(.8*SKALE)
1850 CSIZE 4
1950 LAREL "RAW DATA: ":DTES
1970 MOVE XMAX-5000.1.37*SKALE
1880 CSIZE 4
1390 LABEL "APPROX TEMPERATURE (C)"
1900 MOVE XMAX+1500.-(.95*SKALE)
1910 DEG
1920 LDIR 90
1970 LABEL "AF/F FREQ DEVIATION (10
1940 MOVE XMAX+1600..95*SKALE
1950 LABEL "-8"
1950 MOVE XMAX.0
1970 LINE TYPE 3
1980 DRAW XMIN.0
1990 T=-55
2000 FOR I=0 TO 31 STEP 1
2010 X=XMAX+20-1*(XMAX-XMIN)/31
2020 MOVE X.1.05*SKALE
2010 LABEL T+5*I
2040 MOVE X..95*SKALS
IOSO LABEL "-"
Inau MEXT I
2070 RETURN ! Return to 1030 after plotting CRT frame
1080 PRINTER IS 705 @ PRINT @ PRINT @ DUMP GRAPHICS
2090 GOTO 1080 / Loop back to normal data logging after DUMP GRAPHICS
2100 END
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## MISSION of Rome Air Development Center

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# END

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